

Authenticated Multiuser Quantum Direct Communication using Entanglement Swapping

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Abstract. We present an Authenticated Multiuser Quantum Direct Communication(MQDC) protocol using entanglement swapping. Quantum direct communication is believed to be a safe way to send a secret message without quantum key distribution. The authentication process in our protocol allows only proper users to participate in communication. In this communication stage after the authentication, any two authorized users among n users can communicate each other even though there is no quantum communication channels between them. In the protocol, we need only n quantum communication channels between the authenticator and n users. It is similar to the present telephone system in which there are n communication channels between telephone company and users and any two designated users can communicate each other using telephone line through the telephone company. The securities of our protocols are analysed to be the same as those of other quantum key distribution protocols.

Introduction-One of the objects of quantum cryptography is to allow two distant parties to share a random bit sequence without any reveals to the eavesdropper. The Quantum Key Distribution(QKD) protocols are regarded as unconditionally secure cryptography schemes. The first Quantum key distribution was proposed by Bennett and Brassard. It is known as the BB84 protocol[1], and it uses four different non-orthogonal states of single photon. QKD establishes a common random key between two remote parties of communication. Afterwards these two parties can safely exchange a secret message over the public channel by encoding and decoding them with the distributed key. If the length of the keys is the same as the length of the messages, the communication is unconditional secure. It is because that one-time pad scheme with the enough length of secret key is proved to be unconditionally secure. QKD has progressed quickly since the first QKD protocol was designed[2,3,4,5]. QKD based on quantum mechanics is usually non-deterministic[1,2,3,4,5]. But it is sometimes deterministic[13,14,15], in which two remote parties get the same keys determinately.

A novel concept of quantum direct communication (QDC) has been proposed and pursued recently. Unlike QKD, QDC can directly send secret messages without creating the key to encrypt them. In 2002, Beige et al. presented the first QDC scheme,[6] in which messages can be read after the transmission of classical informations. Bostrom and Felbinger put forward a ping-pong scheme using entangled pair of qubits in 2002[7]. This protocol can be used for QKD as well as QDC. It is secure for key distribution, but is only quasisecondary for QDC even if perfect quantum channel is used. Cai modified the ping-pong protocol by replacing the entanglement states with single photons in mixed state[16]. However it is unsafe in a noisy channel and disadvantaged to the opaque attack.

QDC may have wide application due to its fastness and unconditional security. Our QDC protocol uses entangled states and the entanglement swapping effect. It is well known that quantum entanglement swapping[8] can entangle two quantum systems which did not interact with each other before. But these QDC protocols have a common serious problem. If we don't check whether only proper users communicate each other, secret messages can be exposed to the eavesdropper. It is, thus, important to certify the identities of the legitimate users in communication line so that no third party monitoring their identification can impersonate either of them. In our protocol, Alice (or Bob) can confirm the identification of her (or his) counterpart through the trusted third party, Trent, who acts a role of present telephone company. When one of them wants to communicate with the other, Trent guarantees the identification of each person to his/her counterpart. Afterwards they directly communicate each other using quantum communication channels linking them and Trent.

Our authenticated multiuser QDC scheme using entanglement swapping consists of two parts; quantum authentication mode and quantum communication mode. After finishing authentication mode to identify each other, the messages are transmitted secretly and directly in communication mode.

Entanglement swapping-Let us first describe the quantum entanglement swapping. Let $|0\rangle$ and $|1\rangle$ be the horizontal and vertical polarization states of a photon, respectively. The four Bell states, $|\Phi^\pm\rangle \equiv \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$ and $|\Psi^\pm\rangle \equiv \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$ are maximally entangled states in two-photon Hilbert space. Let the initial state is $|\Phi_{12}^+\rangle \otimes |\Phi_{34}^+\rangle$. We can see that after the Bell measurements on the pair of photon 1 and 3 and the pair of photon 2 and 4, there is an explicit correspondence between the known initial state of the pair of two qubits and its swapped measurement outcomes. The state $|\Phi_{12}^+\rangle \otimes |\Phi_{34}^+\rangle$ can be rearranged as the linear combinations of the terms, $|\Phi_{13}^+\rangle \otimes |\Phi_{24}^+\rangle$, $|\Phi_{13}^-\rangle \otimes |\Phi_{24}^-\rangle$, $|\Psi_{13}^+\rangle \otimes |\Psi_{24}^+\rangle$ and $|\Psi_{13}^-\rangle \otimes |\Psi_{24}^-\rangle$. When the outcome of Bell measurement on the pair of photon 1 and 3 is $|\Phi_{13}^-\rangle$, the Bell state of the pair of photon 2 and 4 must be $|\Phi_{24}^-\rangle$. The outcome of entanglement swapping is summarized in Table 1.

In our protocol, every user sends Trent the secret identity sequence of N -bits. We call the Alice's(Bob's) secret identity as $ID(A)(ID(B))$. It must be kept safely between the user and Trent. Let us introduce the explicit algorithm for the protocol.

Quantum Authentication

Table 1. The outcomes of the swapped Bell measurement on the initially different combinations of four Bell states The abbreviation ID++ represents the set of four possible outcomes of Bell measurement, $(|\Phi_{14}^+\rangle, |\Phi_{23}^+\rangle)$, $(|\Phi_{14}^-\rangle, |\Phi_{23}^-\rangle)$, $(|\Psi_{14}^+\rangle, |\Psi_{23}^+\rangle)$, and $(|\Psi_{14}^-\rangle, |\Psi_{23}^-\rangle)$ with equal probability of 1/4. Similarly, the following cases can be obtained. $ID+- \Rightarrow \{(|\Psi_{14}^+\rangle, |\Psi_{23}^-\rangle), (|\Phi_{14}^-\rangle, |\Phi_{23}^+\rangle), (|\Phi_{14}^+\rangle, |\Phi_{23}^-\rangle), (|\Psi_{14}^-\rangle, |\Psi_{23}^+\rangle)\}$, $Rev++ \Rightarrow \{(|\Phi_{14}^+\rangle, |\Psi_{23}^+\rangle), (|\Phi_{14}^-\rangle, |\Psi_{23}^-\rangle), (|\Psi_{14}^+\rangle, |\Phi_{23}^+\rangle), (|\Psi_{14}^-\rangle, |\Phi_{23}^-\rangle)\}$, and $Rev+- \Rightarrow \{(|\Phi_{14}^+\rangle, |\Psi_{23}^-\rangle), (|\Phi_{14}^-\rangle, |\Psi_{23}^+\rangle), (|\Psi_{14}^+\rangle, |\Phi_{23}^-\rangle), (|\Psi_{14}^-\rangle, |\Phi_{23}^+\rangle)\}$.

	$ \Phi_{34}^+\rangle$	$ \Phi_{34}^-\rangle$	$ \Psi_{34}^+\rangle$	$ \Psi_{34}^-\rangle$
$ \Phi_{12}^+\rangle$	$ID++$	$ID+-$	$Rev++$	$Rev+-$
$ \Phi_{12}^-\rangle$	$ID+-$	$ID++$	$Rev+-$	$Rev++$
$ \Psi_{12}^+\rangle$	$Rev++$	$Rev+-$	$ID++$	$ID+-$
$ \Psi_{12}^-\rangle$	$Rev+-$	$Rev++$	$ID+-$	$ID++$

- (A.0) Authentication process begins when Alice asks Trent that she wants to communicate with Bob.
- (A.1) Trent prepares an ordered set of $2N$ pairs of Bell state of $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. We denote the $2N$ ordered EPR pairs as $[(P_1(T), P_1(A)), (P_2(T), P_2(A)), \dots, (P_N(T), P_N(A))]$ and $[(P_{N+1}(T), P_{N+1}(B)), (P_{N+2}(T), P_{N+2}(B)), \dots, (P_{2N}(T), P_{2N}(B))]$. Here the subscript indicates the ordering number of pairs, and T , A , and B represent the qubits of Trent, Alice and Bob, respectively.
- (A.2) Trent takes one qubit from each EPR pair, say, $[P_1(T), P_2(T), \dots, P_N(T)]$ $[(P_{N+1}(T), P_{N+2}(T), \dots, P_{2N}(T))]$ which is called the $A(B)$ -checking sequence, and keep it safely. The remaining sequence of qubits $[P_1(A), P_2(A), \dots, P_N(A)]$ $[(P_{N+1}(B), P_{N+2}(B), \dots, P_{2N}(B))]$ is called the $A(B)$ -authentication sequence.
- (A.3) Trent encodes $A(B)$ -authentication sequence with Alice's(Bpb's) identification numbers $ID(A)$ ($ID(B)$). If the i -th value of $ID(A)$ is 1, Trent makes an Hadamard operation H to i -th qubit of $A(B)$ -authentication sequence. If it is 0, identity operation I is applied. The results of the operation on $P_i(A)$ is $\{(1 - ID_i(A))I + ID_i(A)H\}P_i(A)$.
- (A.4) Trent sends the $A(B)$ -authentication sequences $[P_1(A), P_2(A), \dots, P_N(A)]$, $[(P_{N+1}(B), P_{N+2}(B), \dots, P_{2N}(B))]$ to Alice(Bob).
- (A.5) The legitimate user, Alice(Bob) knows her(his) ID sequence. She(he) decodes the $A(B)$ -authentication sequence with her(his) ID sequence. The decoding method is the same as the Trent's encoding method. According to the ID sequence, Alice(Bob) makes an Hadamard operation H or does nothing to the qubits of $A(B)$ -authentication sequence. By this decoding operation, the qubits are restored to their original state. Then she(he) measures her(his) sequence in the σ_z basis, and announces the outcomes.
- (A.6) Trent measures the ordered $A(B)$ -checking sequence and compare the results with the Alice's(Bob's) results. If Alice's(Bob's) result is the same as Trent's, then authentication succeeded. Otherwise, authentication failed and abort communication.

Quantum Direct Communication

- (C.1) Alice prepares a random sequence of $M + n + q$ Bell states from two states, $|\Phi^+\rangle_{T_A A} = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ and $|\Psi^+\rangle_{T_A A} = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$. This random choice is Alice's secret information. Bob prepares $M + n + q$ Bell states of $|\Phi^+\rangle_{T_B B} = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. The subscripts of the states represents who is going to keep them after the process of (C.2).
- (C.2) Alice(Bob) takes one qubit from each pair and sends Trent the ordered string of $M + n + q$ qubits which is named as the *A*-sequence(*B*-sequence) hereafter. Alice(Bob) stores the remaining ordered sequence of qubits in a safe place, which is named as *the encoding sequence (the decoding sequence)* hereafter.
- (C.3) Alice randomly chooses n checking positions of the ordered encoding sequence and publicly announces it. Trent measures the n checking qubits of the ordered *A*-sequence by using σ_z basis and tells the outcomes to Alice. Alice measures the corresponding qubits of the encoding sequence by using σ_z basis and compares it with Trent's outcomes. She estimates error rate and can detect a eavesdropper. Bob's checking method is the same as that of Alice and Trent. They can detect eavesdropper on the channel of Alice-Trent or Bob-Trent.
- (C.4) Trent performs Bell measurements on the qubits of the ordered *A* and *B* sequences. In this Bell measurement, Trent does not have to distinguish all of four different Bell states, but only needs to distinguish $|\Phi^\pm\rangle$ and $|\Psi^\pm\rangle$ states. After the Trent's measurement, the encoding sequence possessed by Alice and the decoding sequence possessed by Bob became to be entangled(Entanglement Swapping). Trent sends his measurement outcomes to Alice.
- (C.5) Alice receives the Trent's outcome and measures the encoding sequence with σ_z basis. She randomly chooses q checking positions of the ordered encoding sequence and publicly announces the positions. Bob performs measurement on the corresponding q checking positions of the decoding sequence with σ_z basis and tells the outcome to Alice. Alice can infer Bob's measurement outcome from the effect of entanglement swapping, the information of Trent's measurement outcome, her initial Bell state and her measurement outcome. Alice compares her inference with Bob's corresponding announcements. If there is no eavesdropper on the line, their corresponding results should be correlated. If there is no correlation, the communication is aborted. Table 2 shows the correlations.
- (C.6) According to Alice's bit strings, she publicly announces the positions that Bob needs to flip his measurement outcome on his decoding sequence. As she knows Bob's measurement outcome by using entanglement swapping effect, she can send decoding information to Bob. Bob flips the value of his measurement outcome of the position that Alice informed. Then he can decode the her secret message.

For example, let's suppose that Alice prepares the ordered set of Bell states $\{|\Phi^+\rangle, |\Phi^+\rangle, |\Psi^+\rangle\}$, and Trent's Bell measurement outcomes are $\{|\Phi^+\rangle, |\Psi^+\rangle, |\Psi^+\rangle\}$.

Table 2. The correlation of entanglement swapping

Bob's initial state	Alice's initial state	Trent's Bell measurement outcome	Alice's outcome	Bob's outcome
$ \Phi^+\rangle$	$ \Phi^+\rangle$	$ \Phi^\pm\rangle$	0	0
		$ \Psi^\pm\rangle$	1	1
	$ \Psi^+\rangle$	$ \Phi^\pm\rangle$	0	1
		$ \Psi^\pm\rangle$	1	0
	$ \Psi^+\rangle$	$ \Phi^\pm\rangle$	0	1
		$ \Psi^\pm\rangle$	1	0
	$ \Psi^+\rangle$	$ \Phi^\pm\rangle$	0	0
		$ \Psi^\pm\rangle$	1	1

When Alice's measurement outcomes of the encoding sequence are $\{0, 0, 1\}$, Alice knows that Bob's outcomes must be $\{0, 1, 1\}$. Suppose that Alice's secret message bit is 101. According to the message, Alice publicly announces 110 which designates the positions Bob needs to flip his measurement outcome. After the flipping, Alice's message is transferred to Bob.

Security analysis - The proof of the security of our QDC protocol is based on the security of the transmission of the A - and B -sequence. The state of the transmitted qubits does not contain any information of the secret message because they are completely random and mixed. The exposed information is just random like that of coin flipping. In our protocol, even Trent can not know Alice's secret message since he doesn't know Alice's initial state.

The qubit transmission and the checking method in our protocol is similar to the procedure in BBM92 QKD protocol[10]. Alice stores the encoding-sequence in her safe place, and Eve cannot access it at all. Therefore, the security of our protocol is the same as that of the BBM92 QKD protocol. The proof of security for BBM92 protocol in ideal and practical conditions has been given [11,12]. So our protocol is also unconditionally secure.

Conclusion - We have established the authenticated quantum multiuser direct communication using entanglement swapping. Its security is the same as that of BBM92 protocol, which is unconditionally secure. The encoding of the message is processed only after the authentication of the users and the confirmation of the security of the quantum channel. Our protocol, therefore, is not in danger of exposure of information to Eve. Furthermore the leaked information to Eve is totally random, and does not contain any information.

In this protocol we need only EPR paris. It can be advantage in an experiment. The great feature of our protocol is that any two users among n subscribers can communicate each other. We don't need any quantum channel linking two users, because the center, Trent, connects two users Alice and Bob, and authenticates them. This structure is the same as that of nowadays telephone system, but its security is much better than present technology. It is unconditionally secure. Our scheme may be used for the safe communication system.

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